

Mean p_T scaling with m/n_q at the LHC: Absence of (hydro) flow in small systems?

Antonio Ortiz Velásquez

*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México.
 Circuito exterior s/n, Ciudad Universitaria, Del. Coyoacán, C.P. 04510, México DF.*

Abstract

In this work, a study of the average transverse momentum (p_T) as a function of the mid-rapidity charged hadron multiplicity (N_{ch}) and hadron mass (m) in p-Pb and Pb-Pb collisions at LHC energies is presented. For the events producing low N_{ch} , the average p_T is found to scale with the reduced hadron mass, i.e., mass divided by the number of quark constituents (m/n_q), this scaling also holds for inelastic pp collisions at RHIC and LHC energies. The scaling is broken in high multiplicity p-Pb and Pb-Pb collisions, where, for $\langle dN_{ch}/d\eta \rangle \lesssim 60$ the average p_T is higher for baryons than that for mesons, though they increase linearly with m/n_q . This behavior is qualitatively well reproduced by Pythia 8, but not by hydro calculations, where an universal scaling with the hadron mass (and not with m/n_q) is predicted for all the multiplicity event classes. Only the central (0-60%) Pb-Pb collisions behave as expected from hydro.

Keywords: Multi-parton interactions, color reconnection, flow-like behavior, nucleon-nucleon reactions, nucleon-nucleus collisions.

1. Introduction

The main goal of the heavy ion program is the study of matter under extreme conditions of high energy density, where QCD phase transitions characterized by deconfinement and chiral symmetry restoration (QGP), are expected to occur [1, 2]. To extract the genuine properties of the hot matter, the program includes studies in control experiments, like nucleon-nucleon and nucleon-nucleus collisions, where final state effects were not supposed to be present. Unexpectedly, recent results at the LHC reveal the presence of QGP-like effects, namely, long range angular correlations [3] and flow-like patterns [4] in the systems created in high multiplicity pp and p-Pb collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV, respectively.

Such features of data are qualitatively described by hydro calculations [5, 6], where the formation of a medium and its subsequent fast thermalization are implicitly assumed, but not fully justified. For example, it is known that the validity of a hydrodynamic description requires small values of Knudsen number ($\ll 1$), however, for the systems created in proton-nucleus collisions at $\sqrt{s_{NN}} = 5.02$ TeV, the Knudsen number is already close to one in almost all the space-time points for temperatures $T \lesssim 165$ MeV [7]. Albeit, based on ideas of string percolation [8, 9] it has been argued that deconfinement can also occur in small systems, the origin of the phenomenon has not been established [10]. With the same level of accuracy as hydro, other calculations, which do not require the formation of a mini QGP, also do a good job to describe the data. For instance, color glass condensate (CGC), the QCD formulation on the limit of high occupancy number at low x -Bjorken, predicts the long range angular correlations and their azimuthal anisotropies

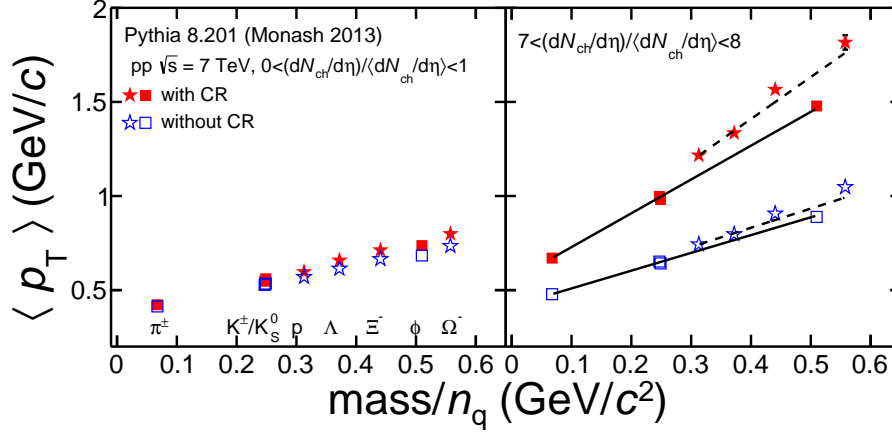


Figure 1. (Color online). Average transverse momentum as a function of the scaled hadron mass (m/n_q) for pp collisions at $\sqrt{s} = 7$ TeV simulated with Pythia 8.201. Two multiplicity event classes are shown, low multiplicity (left) and high multiplicity (right). Results are presented for simulations with (full red markers) and without (empty blue markers) color reconnection. The solid (dashed) line indicates a linear fit to meson (baryon) data.

for even harmonics¹ and for $p_T > 1$ GeV/c; in pp and p-Pb collisions [11]. Recently, it has been demonstrated that anisotropic flow (v_2 and v_3) can be obtained using gluon distributions from classical Yang-Mills simulations of p-Pb collisions [12]. Similarly, the AMPT model reproduces the ridge structure in small systems [13] and Pythia 8 [14] with the tune 4C [15] is able to generate flow-like patterns using color reconnection (CR) and multi-parton interactions (MPI) [16]. It is worth to mention that early LHC results for pp collisions, e.g., the transverse sphericity [17] and the di-hadron correlations [18] as a function of multiplicity, revealed the importance of multi-parton interactions to describe the data.

As discussed here [10], it is important to look at new observables which allow one to establish the origin of the QGP-like effects in small systems. In this context, the present work shows a study of the average transverse momentum (p_T) as a function of the hadron mass (m) and the event multiplicity (N_{ch}) obtained from different measurements reported by experiments at the LHC. Similarities among pp, p-Pb (all multiplicity classes) and peripheral Pb-Pb (60–90%) collisions are found, those effects are qualitatively well captured by Pythia 8, but not by hydro calculations. On the other side, for central Pb-Pb collisions the data exhibit a different feature.

2. Multiplicity dependence of the average p_T vs. hadron mass in Pythia

In Pythia 8, color reconnection and multi-parton interactions produce flow-like patterns in pp collisions at the LHC energies via the creation of boosted strings [16]. To illustrate this, the MC p_T spectra of different particle species ($\pi^+ + \pi^-$, $K^+ + K^-$, K_S^0 , $p + \bar{p}$, ϕ -meson, $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \bar{\Omega}^+$) for pp collisions at $\sqrt{s} = 7$ TeV were studied using Pythia 8.201 [19] (tune Monash 2013 [20]). The transverse momentum spectra and event multiplicity were determined at $|y| < 1$ and $|\eta| < 1$, respectively. It has been shown that the Boltzmann-Gibbs blast-wave function [21] describes within 10% the p_T distributions of all hadrons under consideration when color reconnection is activated [22]. Actually, the ALICE Collaboration has reported the same level of agreement (within $\approx 10\%$) between the data and the blast-wave model for p-Pb collisions [23]. Furthermore, with CR the correlation between the parameters obtained from the fit to MC p_T spectra, the average transverse velocity, $\langle \beta_T \rangle$, and the temperature at the kinetic freeze-out, T_{kin} ; behaves like in data [22, 23]. Namely, $\langle \beta_T \rangle$ increases with increasing the multiplicity density ($dN_{ch}/d\eta$), and at the same time T_{kin} decreases². Hence, the results from the blast-wave analysis are not enough to draw a final conclusion on the possible formation of a strongly interacting QCD medium in high multiplicity pp and p-Pb collisions.

¹The odd harmonics were not generated because rescattering contributions to the intrinsic correlations were not included.

²In simulations without color reconnection, the multiplicity dependence is very weak, i.e., $\langle \beta_T \rangle$ and T_{kin} do not evolve with multiplicity.

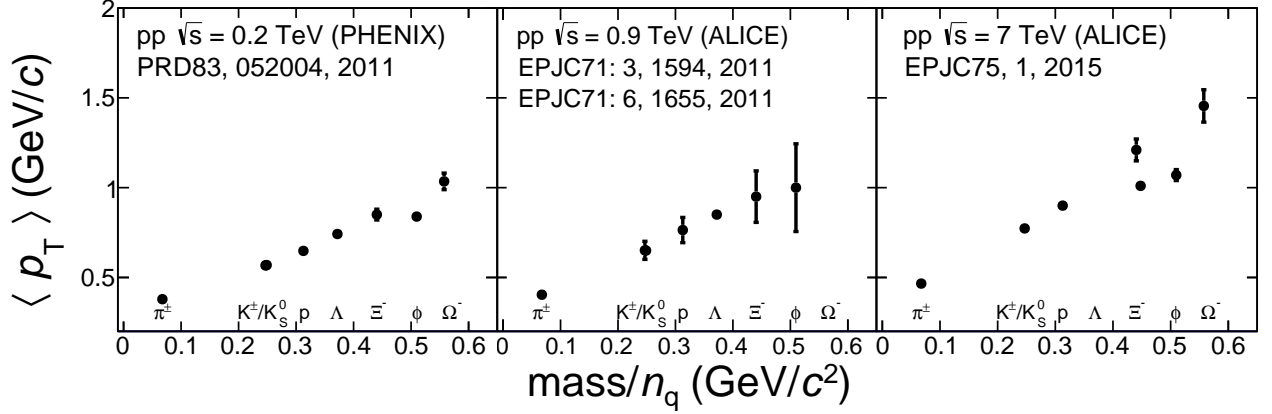


Figure 2. Average transverse momentum as a function of the scaled hadron mass (m/n_q) for minimum bias pp collisions at $\sqrt{s} = 0.2$ TeV (left), 0.9 TeV (middle) and 7 TeV (right) measured by PHENIX and ALICE experiments.

The main focus of this work is the study of the mass dependence of the average p_T . In the string hadronization model, the string boost is transferred to the final particles when the string breaks up and for the same boost velocity a heavy particle will gain more p_T than a lighter one. CR is therefore expected to give a rise of the average p_T vs. hadron mass. Qualitatively, the effect is in good agreement with data, but so far, the current models of CR are not able to reproduce the size of the effect [24]. However, other effects look promising, for example the color ropes formation, which by increasing the effective string tension, can also produce flow-like behavior [25].

The mass dependence of the average p_T has been investigated for two cases, with and without color reconnection. When color reconnection is deactivated, the partonic systems fragment independently, and even in this case, the average p_T increases with the hadron mass. It is worth to remember that in LHC data, even for the lowest multiplicity event class, where a medium is not expected to be formed, the mass ordering is also seen [26–28]. The $\langle p_T \rangle$ increase with the hadron mass, therefore is not a distinct feature of hydro, instead it seems to be a characteristic of the fragmentation. Actually, another observation which is reported for the first time is that Pythia 8.201 without CR produces an average p_T which scales with the reduced hadron mass, i.e., mass divided by the number of quark constituents (m/n_q), and not with the hadron mass:

$$\langle p_T \rangle \propto \frac{m}{n_q}. \quad (1)$$

This is illustrated in Fig. 1, where the correlation between $\langle p_T \rangle$ and m/n_q is shown for two event classes: low ($0 < dN_{ch}/d\eta < \langle dN_{ch}/d\eta \rangle$) and high ($7 \times \langle dN_{ch}/d\eta \rangle < dN_{ch}/d\eta < 8 \times \langle dN_{ch}/d\eta \rangle$) multiplicity. The scaling is valid across the multiplicity event classes, though, it is somewhat violated at high multiplicity. Figure 1 also illustrates the results when color reconnection is activated, in this case, at low multiplicity the scaling holds, while at high N_{ch} it is broken and the $\langle p_T \rangle$ for baryons and mesons increase with different slopes. In addition, the mean p_T for ϕ meson is higher to that for protons, hence, neither a scaling with hadron mass would be expected.

In the hadronization model used in Pythia, the constituent quark number dependence can be built up as follows. Quark - (anti)quark pairs are produced during the string break-up process, a transverse momentum is assigned to the pair following a flavor-independent Gaussian spectrum. Since no string transverse excitations are assumed, the p_T is locally compensated between the quark and (anti)quark of the pair. Each hadron is subsequently formed with the string segments and the total partonic p_T is assigned to the hadron. In this model, a meson corresponds to a small piece of string with a quark in one end and an (anti)quark in the other [29]. This fragmentation is universal, in the sense that is the same for all the primary hadrons produced in the collisions, and therefore a dependence of the average hadron p_T with the constituent quark number is expected to occur. Following the same prescription, in events with large number of MPI and with CR, partons from different origin (MPI, initial state radiation, etc.) are allowed to recombine to form hadrons. This sort of recombination leads to a general n_q dependence of the p_T which becomes

more complex since, as discussed in the previous paragraph, on top of the universal Gaussian fragmentation the string segments are also boosted. In contrast, hydro calculations for small systems [30] give a $\langle p_T \rangle$ which is independent of n_q .

The next sections are dedicated to study the same effects in different colliding systems using published LHC data.

3. Study of $\langle p_T \rangle$ using LHC data

The scaling of $\langle p_T \rangle$ with m/n_q is first investigated in inelastic pp collisions at different center of mass energies, namely, 0.2 TeV, 0.9 TeV and 7 TeV. Data were obtained from different publications of experiments at the RHIC [31] and at the LHC [32–34]. Figure 2 shows the correlation plots, $\langle p_T \rangle$ vs. m/n_q , which are obtained. For 0.2 TeV data, where the event multiplicity is the smallest, $\langle dN_{ch}/d\eta \rangle \approx 2.25$ [35], the m/n_q scaling holds even if heavy hadrons like Ξ^- and Ω^- are considered. The same observation is valid for pp collisions at 0.9 TeV, where the event multiplicity is still small, $\langle dN_{ch}/d\eta \rangle \approx 3.81$ [36]. For the highest center of mass energy, where the identified hadron p_T spectra are available, the scaling is slightly broken as observed in Pythia 8.201 with color reconnection. As in the model, the $\langle p_T \rangle$ for baryons rises faster with the reduced mass than for mesons. Also the average p_T for baryons is higher to that for mesons.

Using the existing ALICE data for p-Pb collisions [26], the average p_T for $\pi^+ + \pi^-$, $K^+ + K^-$, $p + \bar{p}$, K_S^0 and $\Lambda + \bar{\Lambda}$ as a function of m/n_q are obtained and plotted in the upper part of Fig. 3. Two multiplicity event classes are shown, $\langle dN_{ch}/d\eta \rangle = 4.4$ and $\langle dN_{ch}/d\eta \rangle = 45$. As in Pythia 8, for low multiplicity events the scaling of $\langle p_T \rangle$ with m/n_q is observed, while for high multiplicity events it is broken. There, the mean p_T for baryons is higher than for mesons. The analogous analysis for Pb-Pb data [38–40] is presented in the bottom panel of Fig. 3, there, also the ϕ meson $\langle p_T \rangle$ is reported. Like in Pythia 8, the scaling of $\langle p_T \rangle$ with m/n_q is only valid for the most peripheral Pb-Pb collisions (80–90%). For the most central Pb-Pb collisions (0–5%), the mean p_T for baryons and mesons as a function of m/n_q exhibit different trends. In addition, for this event class the average p_T for protons is roughly the same to that for ϕ mesons. This observation triggers the question of whether a scaling of $\langle p_T \rangle$ with mass, and not with m/n_q , is seen in the most central Pb-Pb events.

The possible universal scaling with m is investigated, Figs. 4 and 5 show the multiplicity dependence of the average p_T as a function of the hadron mass for p-Pb and Pb-Pb collisions, respectively. The universal mass scaling is only observed in the 0–60% centrality classes for Pb-Pb collisions. While, it is broken for the rest of the Pb-Pb centrality classes (60–90%) and for all the multiplicity classes measured in p-Pb collisions. In Fig. 4, also hydro calculations for p-Pb [30] are shown, there, the mass scaling holds for all the multiplicity classes.

One thing which can be seen is that for the same multiplicity density, $\langle dN_{ch}/d\eta \rangle \approx 35$, the slope of $\langle p_T \rangle$ vs m is higher in p-Pb than in Pb-Pb collisions. This can be quantified if a first degree polynomial is fitted to data, in this exercise the correlations $\langle p_T \rangle$ vs m/n_q for p-Pb and Pb-Pb data were used. Figure 6 show the results for mesons, where the slopes obtained from the fits are plotted as a function of the event multiplicity. For comparison, also the results for inelastic pp collisions at different center of mass energies are shown. At low multiplicity, where the universal scaling of $\langle p_T \rangle$ with m/n_q is approximately valid, the data points from all the systems follow the same trend, and then, for higher multiplicities, p-Pb and Pb-Pb data deviate.

4. Conclusions

Collectivity is considered one of the key ingredients to establish the formation of an equilibrated QGP. So far, the way to verify whether a system behaves collectively or not relies in the success of the hydro models to describe flow observables. Namely, the p_T distributions of identified hadrons and v_n , which are connected with radial and anisotropic flow, respectively. In the present work the details of existing p_T spectra for different colliding systems were studied aiming to check two things. On one side, how precise hydro models describe data, specifically, to check in data the mass scaling of the average p_T as predicted by hydro [30]. And on the other side, to test an alternative explanation based on color reconnection and multi-parton interactions. This investigation brought the following results:

- Low multiplicity pp collisions simulated with Pythia 8 exhibit an universal scaling of $\langle p_T \rangle$ with m/n_q (mass divided by the number of quark constituents). When CR is switched-off, the effect does not depend on multiplicity. In the opposite case, this universal scaling is broken, i.e., a deviation from the linear behavior is observed, and the average p_T for baryons and mesons increase following different lines.

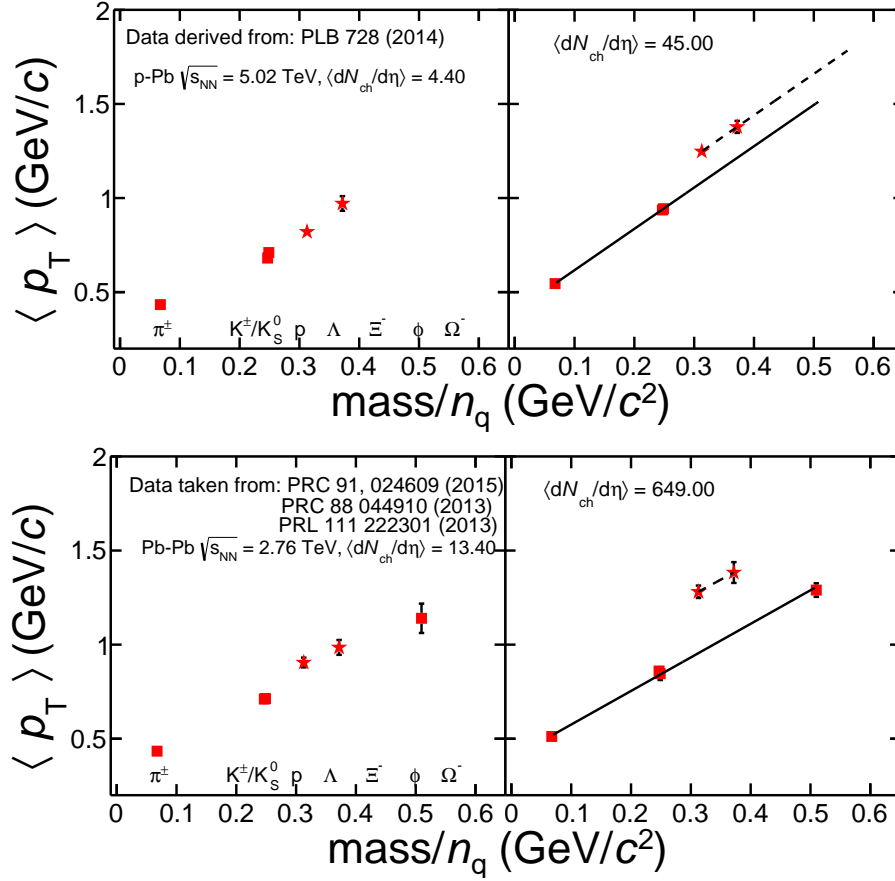


Figure 3. (Color online). Average transverse momentum as a function of the hadron mass normalized to the number of constituent quarks. Results for the lowest and highest multiplicity event classes in p-Pb collisions are shown in the upper panel. For Pb-Pb collisions, the results for the most peripheral and the most central events are shown in the bottom panel. The solid (dashed) line indicates a linear fit to meson (baryon) data. The average multiplicity densities, $\langle dN_{ch}/d\eta \rangle$, for the different event classes have been measured by ALICE in $|\eta| < 0.5$ [26, 37].

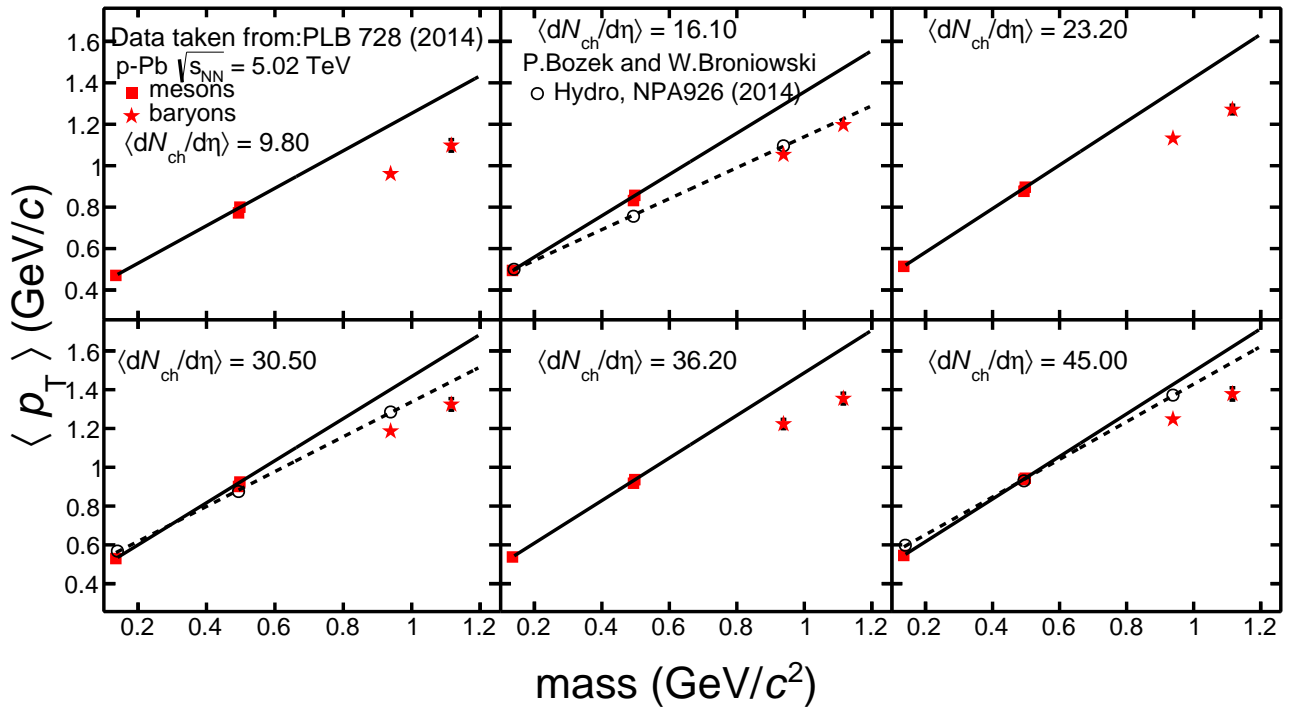


Figure 4. (Color online). Multiplicity dependence of the average transverse momentum as a function of the hadron mass in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (solid markers). A first degree polynomial (solid line) is fitted to the meson data. For three multiplicity classes, hydro calculations [30] are also shown (empty markers), linear fits to meson $\langle p_T \rangle$ calculations are shown as dashed lines. The average multiplicity densities, $\langle dN_{ch}/d\eta \rangle$, for the different event classes have been measured by ALICE in $|\eta| < 0.5$ [26].

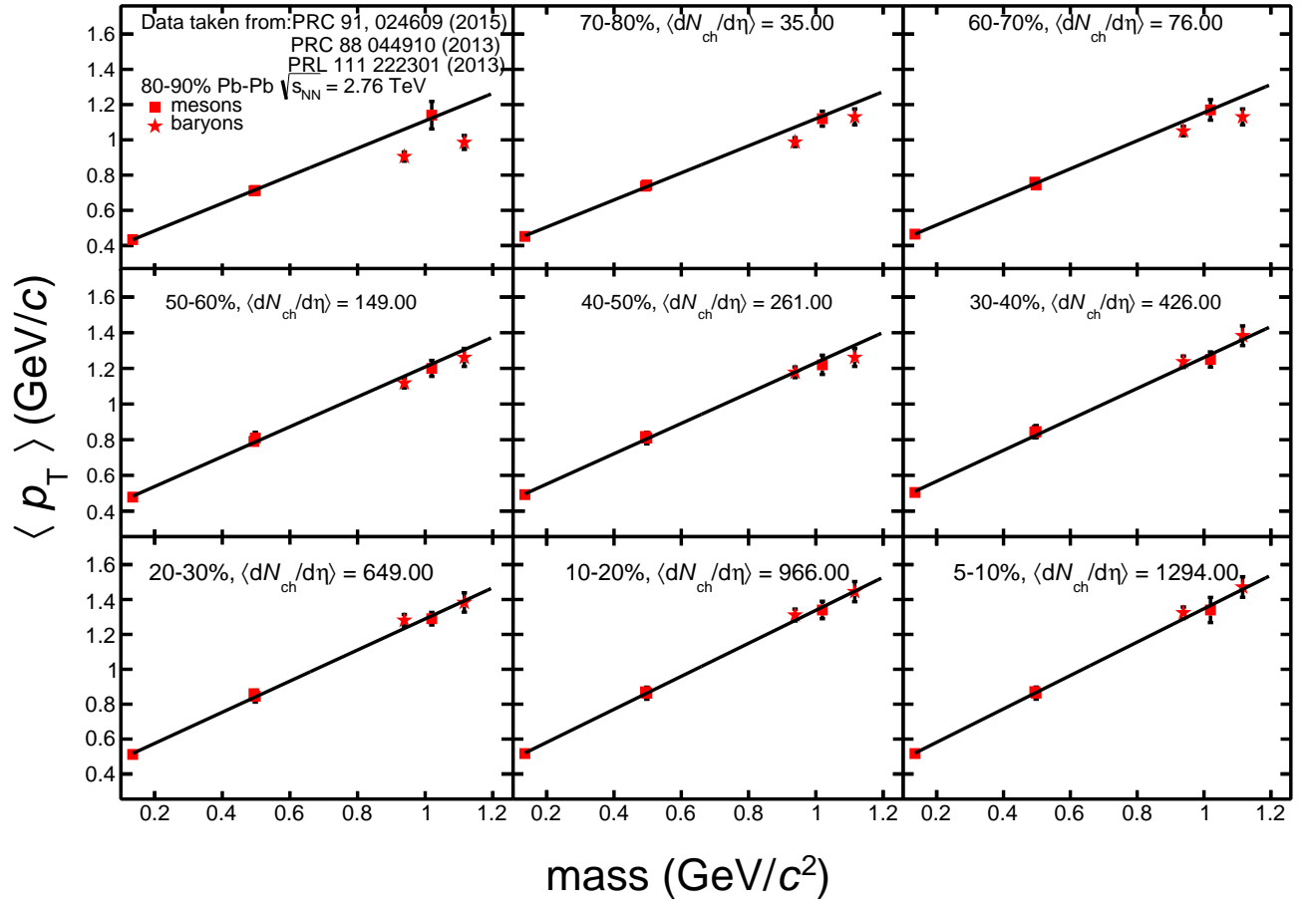


Figure 5. (Color online). Centrality dependence of the average transverse momentum as a function of the hadron mass in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Solid line indicates the first degree polynomial which fits the meson data. The average multiplicity densities, $\langle dN_{ch}/d\eta \rangle$, for the different event classes have been measured by ALICE in $|\eta| < 0.5$ [37].

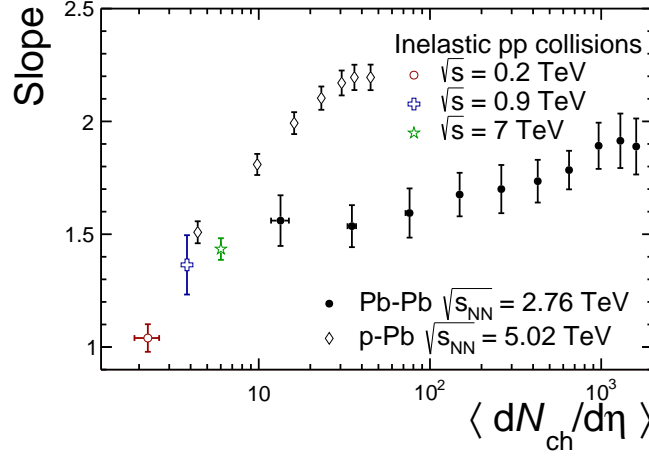


Figure 6. (Color online). For each event class, a first degree polynomial is fitted to the average p_T vs. the reduced hadron mass (m/n_q). In this figure, the slopes extracted from the fits are plotted as a function of the event multiplicity for different colliding systems.

- LHC data for p-Pb collisions as a function of the event multiplicity give results which are qualitatively similar to those observed in Pythia 8. The same observation holds for inelastic pp collisions at RHIC and LHC energies.
- For LHC Pb-Pb data the average p_T as a function of mass shows an interesting phenomenon. Up to centralities of about 50-60% the baryon and meson $\langle p_T \rangle$ do not scale with the same dependence (similar to the results obtained with Pythia). For more central collisions the scaling with mass seems to work.

The results imply that the application of the hydro model should be done with great care because the scaling with mass is not an universal behavior of the data. The hydro model assumes that the behavior of all particles in the mostly pion cloud created after the collision is identical. However, without taking into account the difference in the pion - particle interaction cross section (as was observed at SPS and RHIC energies for the slope). Again the results of Pythia simulations surprisingly well reproduce the different behavior of mesons and baryons raising the possibility of an altogether alternative interpretation.

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